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INVESTIGATION OF THE CONCEPT OF DIRECT FLIGHT CONTROL

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by

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I. SUMMARY

A system which provides direct and independent control of flight path speed, heading, and angle with the horizon was synthesized and evaluated in an analog computer simulation. Performance by subjects whose piloting experience varied from zero flight hours to four thousand flight hours was compared using direct control and conventional control systems. Two primary results were obtained: first, the performance of a subject with no flight experience using direct control was equal or superior to the performance of a subject of 4,000 hours experience using conventional controls, performance being measured in terms of mean square deviation from a proscribed flight path; second, performance improvement varied inversely with pilot experience. The resulting control scheme utilized closed-loop devices with emphasis placed on simplicity and reliability.

SYMBOLS

α	airplane angle of attack
γ	flight path angle measured from the horizontal
$\delta_{a, r}$	deflection of aileron and/or rudder
δ_e	deflection of the elevator
δ_F	deflection of the wing flap
δ_T	displacement of the engine throttle
$\Delta\gamma$	increment in γ
ρ	atmospheric density
ϕ	airplane bank angle
ψ	angle of heading

C_D	airplane drag coefficient
C_L	airplane lift coefficient
C_T	thrust coefficient
$f_i(x)$	the ith function whose argument is x
F	a matrix
g	gravitational acceleration
M	test mass of a linear accelerometer
q	angular rate about airplane body axis y
$\bar{q}$	dynamic pressure $\left(\frac{1}{2}\ \rho V^2\right)$
r	angular rate about airplane body axis z
V	flight path speed
$\dot{x}$	$\dfrac{\partial x}{\partial t}$

II. INTRODUCTION

The task of piloting a conventional aircraft consists
of two separate portions: decision-making or exercising
judgement as to a desired flight path, and proper mixing
of the available flight controls to achieve the desired
path. It is postulated that if the pilot could be relieved
of the second part of the task, concentration on decision-
making would result in a shorter training period for learning
to fly and better performance for experienced pilots. A
constraint on the solution to accomplish this is that the
goal is to be realized as a primary control system for a
low-cost (under $10,000) personal aircraft. This means
minimization of complexity and maximization of reliability.

The Problem

The path of an aircraft is defined by the time history
of the velocity vector associated with the airplane motion.
From a pilot's viewpoint it is convenient and useful to
specify three quantities to determine a flight path: path
angle measured above or below the horizon (γ), azimuthal
path angle measured with respect to north (ψ), and path speed
(V). As a system for controlling these variables, the con-
ventional aircraft uses (1) an aerodynamic surface to introduce
motion about the pitch axis, thus changing angle of attack (α)
of the wing to alter lift and drag forces; (2) other aerodynamic
surfaces to cause rolling motion which tilts the wing lift

force, thus introducing a turning rate; and (3) a throttle

for changing longitudinal force, thus causing changes in

the major component of path speed. If a vector matrix

mathematical model is constructed for illustration, we might

write

$$\begin{vmatrix} \alpha \\ \psi \\ V \end{vmatrix} = [F] \begin{vmatrix} \delta_e \\ \delta_{a,r} \\ \delta_T \end{vmatrix} \qquad (1)$$

The path variables on the left are related to control actions

(represented by the vector on the right whose elements are

elevator deflection, δ_e, aileron and rudder deflection, $\delta_{a,r}$,

and tl-ottle position, δ_T) by the matrix F*. If the matrix

F was composed of only elements on the diagonal, the pilot's

task would be simple in that one of the control elements would

effect one and only one of the path variables. Unfortunately,

such is not the case for a real airplane. In fact, learning

to fly a real airplane consists of learning to develop the

proper values for all the elements of F. The elements of F

vary somewhat from airplane to airplane, which is what pilots

mean by saying that a B-52 "handles differently" from a Cessna

180. The task at hand is to provide a control scheme which

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*This presumes the variables are linearly related to the control
inputs, which may or may not be so. This notation is to be used
only to illustrate the problem and not for any computation.

effectively diagonalizes F and controls γ rather than α.
The pilot is to be given a separate control to change γ,
a separate control to change ψ, and a separate control to
change V. These controls will replace those which comprise
the control vector in Eq. (1).

The Method of Attack

Because of the constraint of requiring simplicity and
reliability of the control scheme, open-loop control will
be utilized wherever possible. If the attendant performance
is unsatisfactory, closed-loop control methods will be sought,
using as a priority those systems which depend on variables
which are most easily measured. In modern control system
theory this corresponds to designing a control by commencing
with "the observable state variables."

Should closed-loop controls be required to provide
adequate performance, use of the pilot's judgment will be
included in the feedback loop to simplify the control. As
an example, calibrated controls--those where a given position
of a control lever is labeled with a specific value of the
variable it controls--will be avoided. Instead, suppose a
velocity control is mechanized which, when its position is
changed, alters only V. We seek to make this control function
so that control movement in one direction causes monotonic
changes in V, but not necessarily in a specific or linearly

proportional amount. For a desired value of V, the pilot would monitor an airspeed indicator to determine a match between control position and V in the steady state. It is in this sense that the pilot would serve to assist in closing the control loop. For a fixed control lever position the last value of the variable being controlled will be maintained.

Finally, the problem will be considered in two parts: control of Y and V (motion in the vertical plane) in one section, and control of ψ (motion in the horizontal plane) in another section. Coupling of the two control modes will complete the analysis.

III. DEVELOPMENT

Control of Y and V

For analysis of motion in the vertical plane, ψ will be considered constant and the airplane assumed to be in a wings-level, zero sideslip condition at all times. Then the locus of points which constitute equilibrium flight condition for combinations of Y and V define the shaded surface shown in Figure 1.* We wish a control scheme which permits movement on this surface in any desired direction. If direct, independent control is to be realized, movement of the Y-control must cause the aircraft operating point to move on a particular line belonging to the surface; namely, the line

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*At a given aircraft gross weight and for V measured in indicated airspeed at any density altitude.
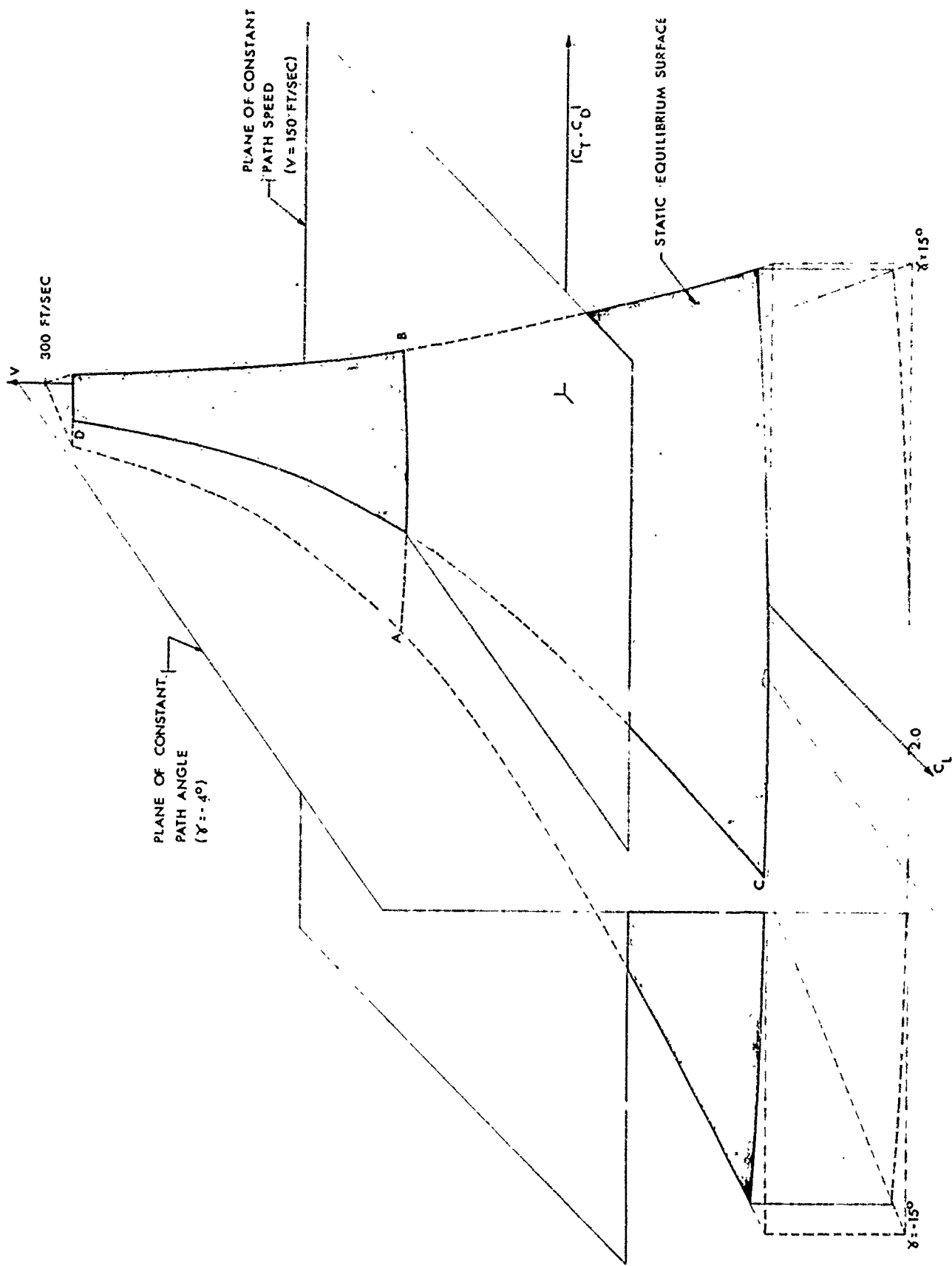
FIG 1 STATIC OPERATING SURFACE

PLANE OF CONSTANT PATH SPEED (V = 150 FT/SEC)

300 FT/SEC

(C_T, C_D)

STATIC EQUILIBRIUM SURFACE

$\gamma = 15°$

$\gamma = -15°$

C_L

2.0

V

B

A

D

PLANE OF CONSTANT PATH ANGLE ($\gamma = -4°$)

C

resulting as the intersection of a horizontal plane (representing some constant value of V) and the shaded surface. A-B is such a line. Similarly a velocity control must alter V at a constant value for γ, such as the locus represented by the curve C-D.

During periods of accelerated flight the instantaneous operating point departs from the shaded surface. An acceptable control system must provide satisfactory aircraft behavior during the period of returning to equilibrium flight, that is, while moving from one point to another on the surface.

The equations defining the shaded surface are

$$\gamma = \tan^{-1} \frac{C_T - C_D}{C_L} = \frac{C_T - C_D}{C_L} \tag{2}$$

$$V = \left(\frac{W \cos \gamma}{\rho/2 \ S \ C_L}\right)^{1/2} \tag{3}$$

Elements in Eqs. (2) and (3) which determine γ and V are functions of these flight and control parameters:

$C_T = f_1$ (engine-propeller combination, i.e., power controls settings, and density altitude)

$C_D = f_2$ (airplane angle of attack, α, and wing flap deflection, δ_F)

$C_L = f_3 \ (\alpha, \ \delta_F)$

$\rho = f_4$ (altitude)

$W = f_5$ (payload, fuel)

Considering for the moment ρ and W to be constants, Eqs. (2) and (3) can be written

$$\gamma = \frac{f_1 (\delta_T) - f_2 (\alpha, \delta_F)}{f_3 (\alpha, \delta_F)} \tag{4}$$

$$V = K \left[\frac{\cos \gamma}{f_3 (\alpha, \delta_F)}\right]^{1/2} = K \left[\frac{\cos \left(\frac{f_1 - f_2}{f_3}\right)}{f_3}\right]^{1/2} \tag{5}$$

Neither γ nor V appear to be affected separately by just one of the functions f_i. The interrelation of the functions infer that any mixing scheme will need to be somewhat complex to accomplish independent control. However, it is reasonable to restrict the total range of γ to $\pm 10°$* and as a consequence changes in the value of f_1 while holding f_2 and f_3 constant cause significant bipolarity changes in γ while affecting V only slightly. This suggests the use of throttle as a path control and α and/or δ_F as a velocity control. If this is to be done, keeping γ constant while changing V will necessitate coupling δ_T with α and δ_F to counteract changes in f_2 and f_3 in Eq. (4). Another difficulty occurs, caused by the need to maintain constant α while varying γ: th s virtually requires sensing and closed-loop control of α.

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*As shown for even STOL aircraft in Ref. 1, 2.

To see if these complexities are justified by the performance this scheme produces, an analog computer simulation was mechanized according to the block diagram shown in Fig. 2.
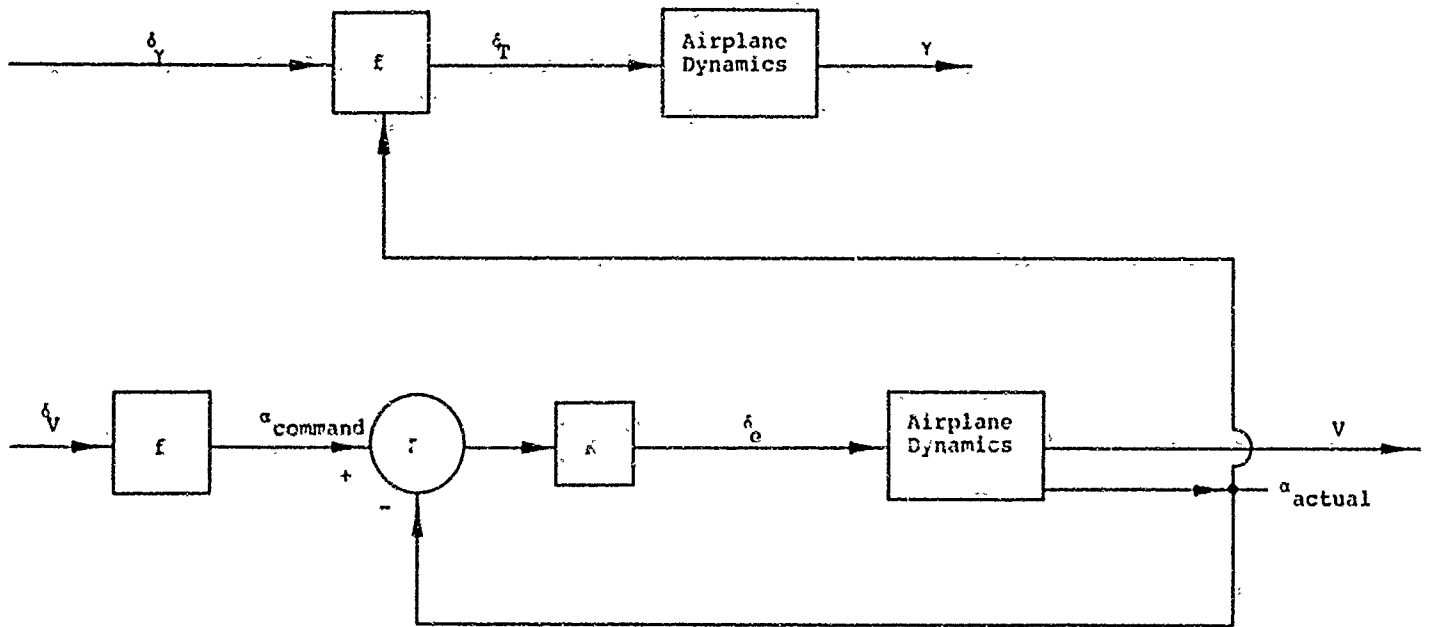

FIG. 2 - PROPOSED CONTROL SCHEME UTILIZING α-COMMAND AND THROTTLE

Flight test data for a Cessna 180 was used to construct a non-linear mathematical model. Compensation of δ_T to maintain constant Υ as described above was done by incorporating a model of the airplane drag polar into the control scheme. Not only was this method involved but an additional difficulty was revealed. Although the static solutions afforded were satisfactory, an attempt to change status invariably excited

the long-period, poorly-damped longitudinal oscillation (phugoid mode) characteristic of this type of aircraft. Sample time histories which demonstrate this behavior are shown in Fig. 3. In consideration of these shortcomings, this scheme was discarded.
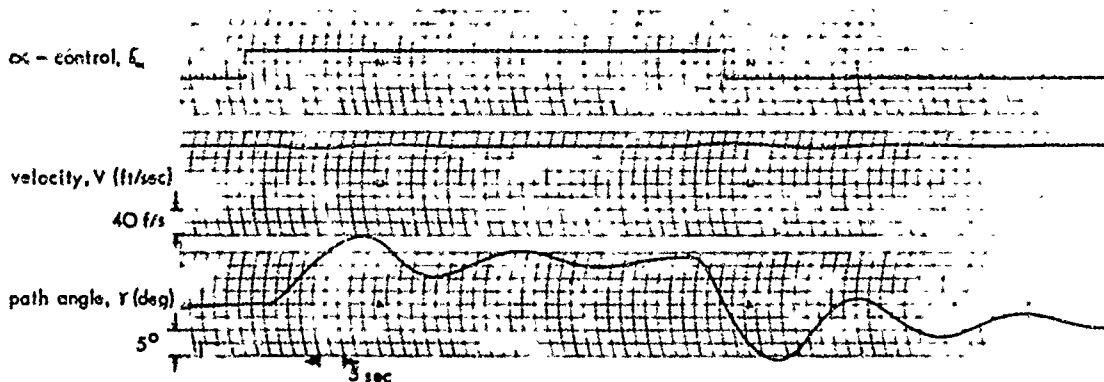

FIG. 3 - DYNAMIC BEHAVIOR OF PROPOSED α-THROTTLE CONTROL SCHEME

Returning to the equations, it is worthwhile to consider attempting what is apparently the most difficult method of control--use of closed-loop systems which command γ and V. To begin with, measurement of γ is not easily accomplished. Path angle can be measured either by

$$\gamma = \theta - \alpha \tag{6}$$

or by

$$\gamma \cong \frac{\text{vertical speed}}{\text{path speed}} \tag{7}$$

If the relationship of Eq. (6) is used, both pitch attitude and angle of attack must be measured and their difference formed to determine γ. In Eq. (7), vertical path speed is not quickly measured plus a quotient must be formed. Such complexities are what we wish to avoid. As to measuring velocity, true airspeed requires computation based upon dynamic pressure measurement and air density measurement.

As a compromise solution, we might provide control of two variables slightly removed from γ and V: $\dot{\gamma}$ and q, dynamic pressure. If we are successful, this will mean a change in the way a pilot uses the controls. First, a lever which controls $\dot{\gamma}$ rather than γ would be displaced from a neutral position only while the pilot was changing path angle. When this lever is returned to a neutral position, $\dot{\gamma}$ would be maintained at zero thus sustaining the last value of γ. The pilot would be required to do something only when he wished to change path. Second, a lever to control q rather then V would provide a command for indicated airspeed instead of true airspeed. The merits and demerits of this subsitution are largely subjective and dependent upon pilot opinion. Certainly it could be no worse than the conventional control system where the pilot flies by indicated airspeed completely.

Both $\dot{\gamma}$ and q are relatively simple to measure. For q, a spring bellows will produce a displacement proportional to q. For $\dot{\gamma}$, an accelerometer mounted to be sensitive to

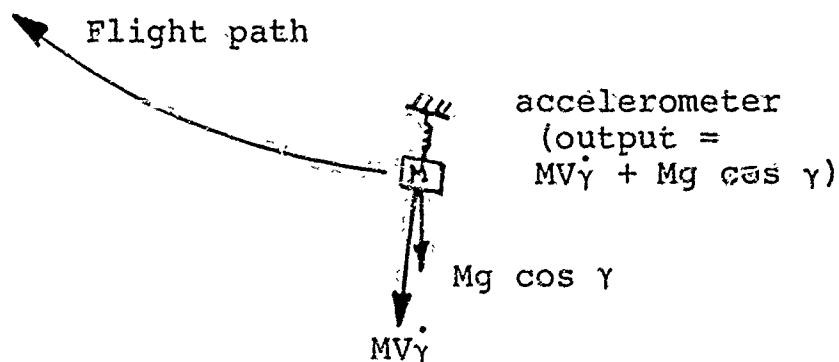acceleration normal to the flight path will measure something which includes $\dot{\gamma}$:

FIG. 4 - ACCELERATED FLIGHT MEASUREMENT

If level flight load factor of one is subtracted from the accelerometer output, the difference between the output and $MV\dot{\gamma}$ is $Mg (1 - \cos \gamma)$. Consequently, the accelerometer measures true normal acceleration only when $\gamma = 0$. Seriousness of this error can be ascertained by integrating the equation

$$V \frac{d\gamma}{dt} = + g (1 - \cos \gamma) \tag{9}$$

Bounds on the error are seen to occur where γ @ $t = 0$ is greatest and V is least, as in a landing approach or takeoff climb. For $\gamma_{t=0} = 0.1$ RAD and V = 100 ft/sec., $\Delta \gamma = .03$ RAD after 15 seconds. Since it is unlikely that a pilot would

fly "hands-off" for 15 seconds during this type of maneuver,
the error is not serious. A more represe tative test case
is cruising flight conditions where it is desirable to pay
little attention to controlling the aircraft. Then, for
$\gamma_{t=0} = .06$ RAD and V = 250 ft/sec, $\Delta \gamma = .003$ RAD after 30
seconds. Of course the nearer level flight the aircraft
is initially the less the cumulative error.

It is better to command a value of the product $V\dot{\gamma}$
than a value of $\dot{\gamma}$ alone because the need for a large size
$\dot{\gamma}$ occurs only at low V while at high V small $\dot{\gamma}$ values suffice.
Furthermore, this product represents load factor normal to
the flight path, a quantity to which pilot, passengers, and
the aircraft structure is sensitive. Since the control scheme
provides control of $V\dot{\gamma}$ at constant V, it actually functions
as a $\dot{\gamma}$ control with a sensitivity inversely proportional to
velocity.

A system based upon controlling these two variables
was synthesized in an analog simulation according to the
block diagram of Fig. 5. As a test of this system, control
inputs were applied one at a time to determine the degree of
separation between γ and V changes. The sequence of operation
was this:

>   Part A - From an initial condition of level flight at
>   250 ft/sec, step function movement of the γ-
>   control to reduce speed while maintaining level
>   flight ($\gamma = 0$).
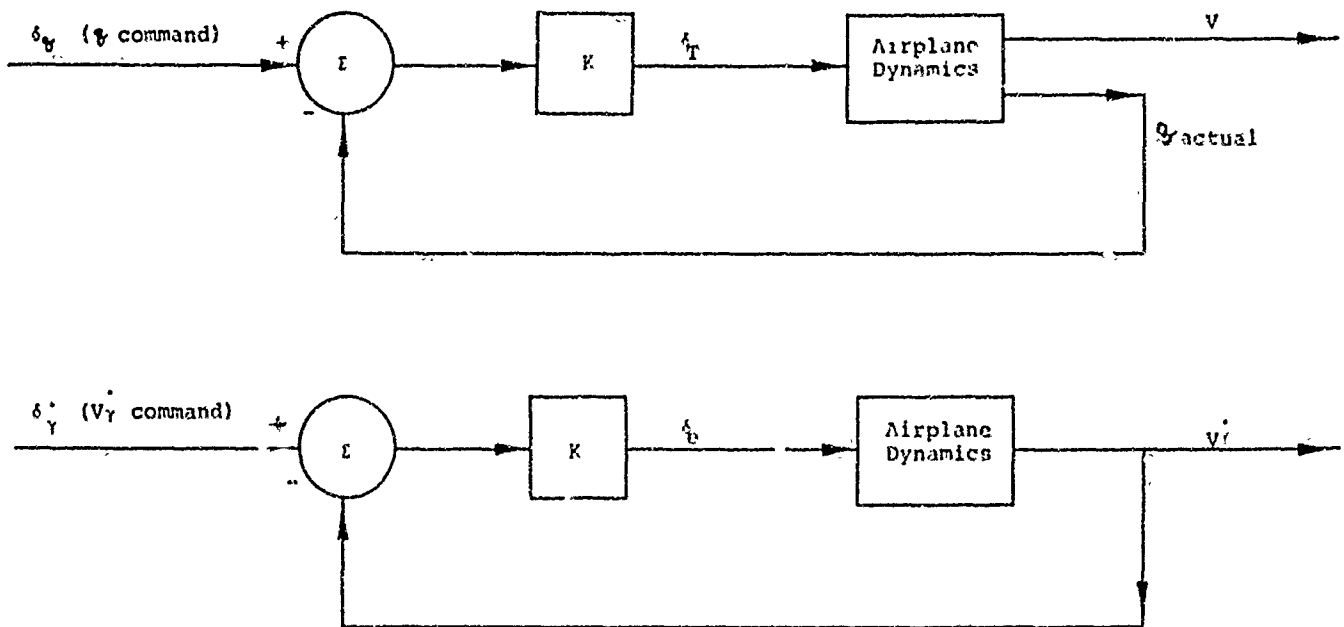
FIG. 5 - PROPOSED VẎ-$\dot{\gamma}$ CONTROL SCHEME

Part B - A pulse displacement of the $\dot{\gamma}$ control to transition from level flight to a descent angle while maintaining constant V.

Part C - A reverse pulse displacement of the $\dot{\gamma}$ control to return the path angle to zero.

Part D - A period of level flight with no control action

Part E - Transition to a climb angle

Part F - Return to level flight

Part G - Acceleration to original velocity during level flight.

Figure 6 presents time histories of V, h, δ , and $\delta_{\dot\gamma}$.
The second trace is altitude, a measure of the integral of
γ:

$$h = \int_0^t \gamma \, V \, dt$$

Moderate values of forward loop gain in both the $\dot\gamma$ and
systems were used, with the result in a maximum excursion
of V from the desired value at any time of $\pm$ 6 ft/sec and
an excursion of 50 ft in h while $\dot\gamma$ was held at zero. The
error in h reflects the difficulty in estimating when
$\gamma = 0$ is reached by using an altimeter for information and
a $\dot\gamma$ control. A sensitive, fast-acting rate of climb instrument
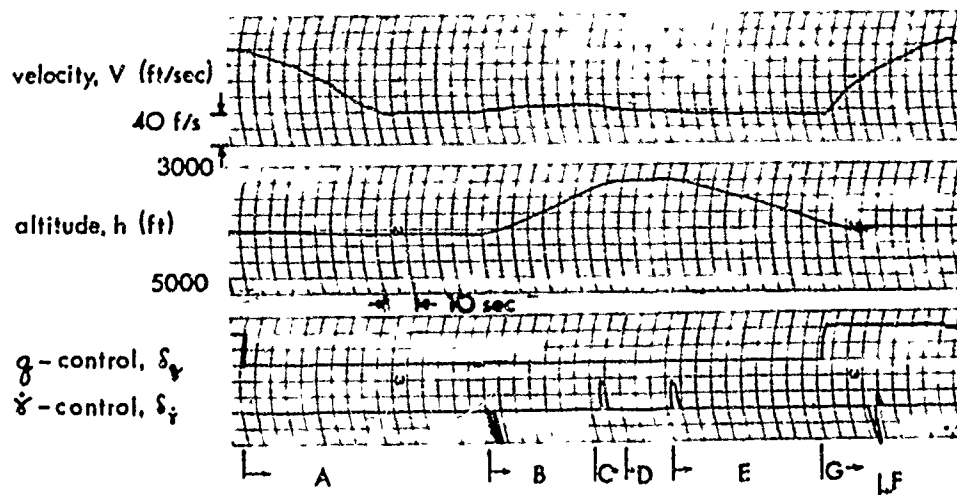produced better results.

FIG. 6 - DYNAMIC RESPONSE TO INDIVIDUAL INPUTS IN $\dot\gamma$-γ CONTROL SYSTEM

The scheme was considered good enough to test with a
more elaborate simulation and three test subjects: a person
with no flight experience, a pilot with 100 hours total time,
and a pilot with 4,000 hours total time. Results are pre-
sented in detail in Section IV.

Control of ψ

For fixed-wing aircraft, the only method of producing
a turning flight path is to tilt the largest aerodynamic
force vector, lift, so as to produce a lateral force com-
ponent of sufficient size. This means tilting the entire
aircraft, that is, banking the airplane. The dynamics of
turning flight lead to spiral maneuvers, and problems with
providing inherent spiral stability for personal aircraft
have long been troublesome to the designer. Compromises
in either performance or cost and complexity appear to be
necessary to achieve stability in turning maneuvers. The
Mooney Aircraft Company recently adopted full-time automatic
stabilization of the roll axis as standard equipment on one
of their aircraft. A closed-loop control system with rate
gyro sensing is used in their method with a demonstrated
reliability sufficient to win Federal Aviation Agency approval
as a primary control system.

In this study an open-loop method of controlling heading
was attempted with no success. It is believed that the merits
of a system such as that of the Mooney Company outweigh the
cost* and complexity of the device. Consequently a rate gyro
sensed, aileron actuated control which commands $\dot{\psi}$ was inves-
tigated. No difficulties were encountered in achieving

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*Interestingly, Mooney incorporated the control system at no
increase in retail cost of the airplane.

excellent performance by application of standard control

system design techniques. The resulting scheme is diagrammed
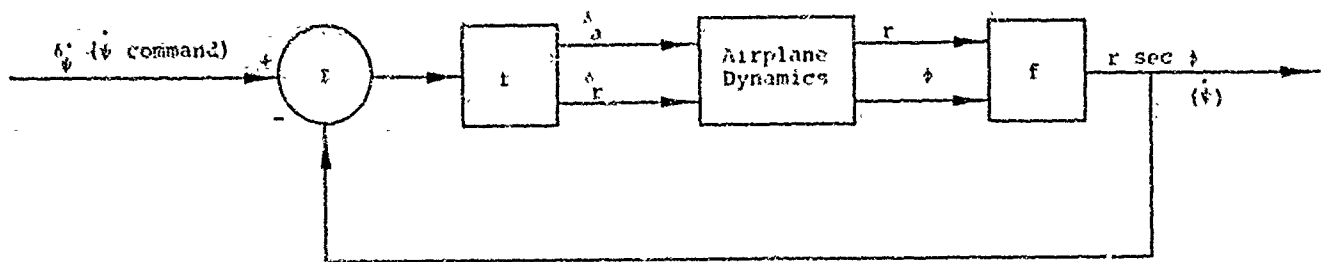
in Fig. 7.

FIG. 7 - PROPOSED $\dot{\psi}$ CONTROL SCHEME

Coupling the Two Controls

Coupling of the equations of motion for longitudinal

dynamics and lateral-directional dynamics resolves into a

single problem for the class of aircraft being studied:

equilibrium in steady state turns. In Fig. 8, angular

motion about a body axis coordinate system is measured by

the accelerometer output used in the $\dot{\gamma}$ control (which is

constrained to tilt with the aircraft in roll), along with

the rate gyro used to sense r in controlling $\dot{\psi}$. These

angular rates can be expressed in components along the

local earth vertical and along a horizontal axis perpendicular
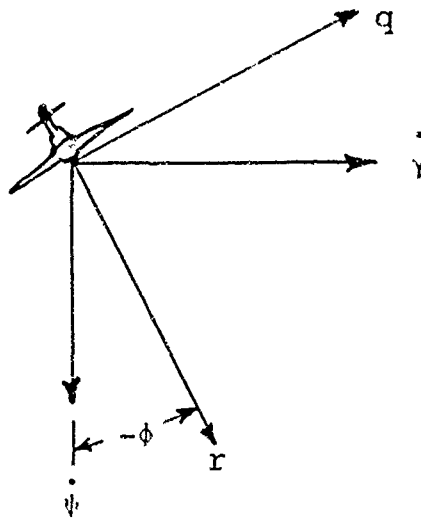
to the flight path:

FIG. 8 - TURNING FLIGHT ANGULAR RATES

$$\dot{\psi} = r \cos \phi + q \sin \phi \tag{10}$$

$$\dot{Y} = -r \sin \phi + q \cos \phi \tag{11}$$

r is measured by rate gyro

$$q \cong \frac{\text{accelerometer output}}{V}$$

Since we wish to not cause a change in Y when changing ψ, we couple the two parts of the control scheme by sending the $\dot{Y}$ control a compensating signal during turning flight. This signal is determined by equating $\dot{Y} = 0$

$$\dot{Y} = 0 = -r \sin \phi + q \cos \phi \tag{12}$$

so

$$q_{correction} = r \tan \phi \qquad (13)$$

$$V\dot{\gamma}_{correction} = V r \tan \phi \qquad (14)$$

Under the constraint of $\dot{\gamma} = 0$, turning rate becomes

$$\dot{\psi} = r \sec \phi \qquad (15)$$

which was the reason for the appearance of that term in the $\dot{\psi}$ control.

Now and in the $\dot{\psi}$ control system we have presumed that information about bank angle, ϕ, was available. Even in the lowest cost aircraft, attitude gyros are generally installed and are likely to become more common in the future.

If the added complexity of multiplying the V in correcting $\dot{\gamma}$ is considered too elaborate, a good compromise can be made by assuming a value for V in the most critical range, probably in cruising flight, and using it as a multiplicative constant.

Thus the total control system diagram would be as shown in Fig. 9. The original task of having three inputs to command directly the three outputs is indicated in the block diagram.
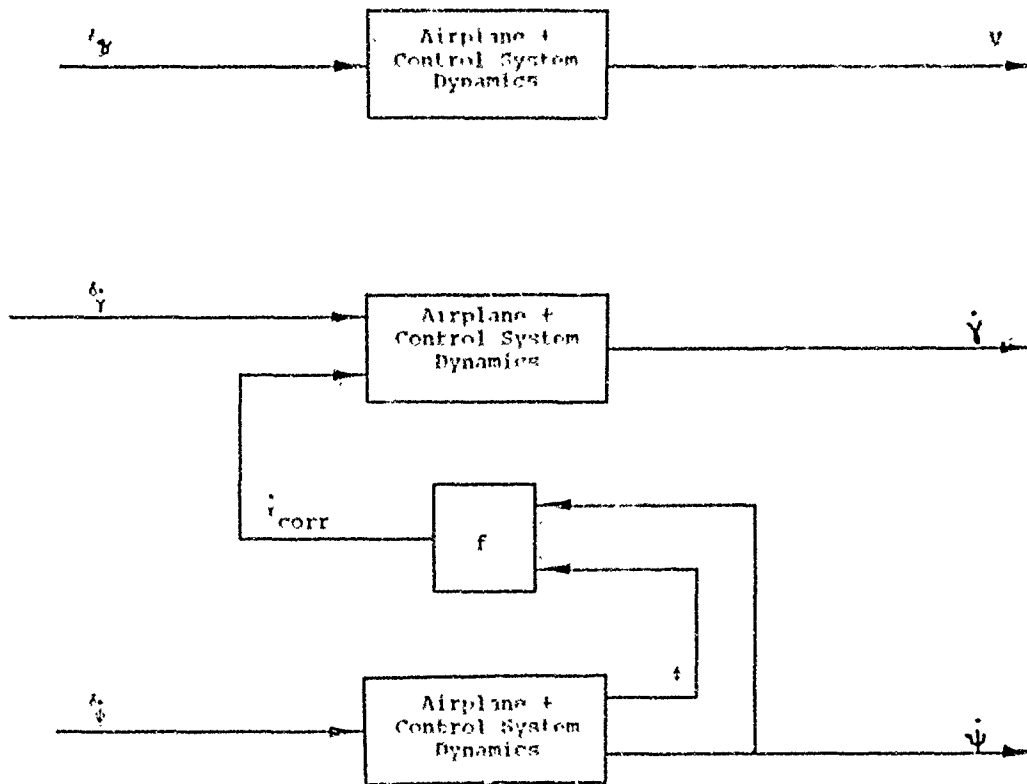
FIG. 9 - COUPLING OF THE $\dot{\gamma}$-q AND $\dot{\psi}$ CONTROL SYSTEMS

Summary Features of the Scheme

A. <u>Separation of Control Functions</u> - excellent, can
be improved with increased loop gains, requires no
compensation in forward or feedback loops.

B. <u>Complexity</u>

1. Sensing Devices Required

a. Spring bellows for q-sensing, can also be
made large enough to actuate the throttle
without amplification devices.

b. Accelerometer for $V\dot{\gamma}$ sensing, mounted on
a vane device to sense along wind axes.

   c. Rate gyro, mounted to sense along body

     axis z

   d. Attitude gyro - presumed already in air-

     craft, used to obtain ϕ information.

  2. Computation Required

   a. Determination of the product $r \tan \phi$

     and $r \sec \phi$, possibly available simply

     with non-linear resistance pickoffs on

     ϕ-gyro.

   b. Summing devices to form error signals

     in the closed loops.

  3. Servo Amplification and Actuation Required

   a. One for elevator actuation

   b. One for aileron actuation, probably with

     interconnected rudder actuation to counter-

     act yaw.

C. Reliability as a Primary Control System -

Dependent upon the degree of redundancy incorporated,

which is dependent upon the desired cost-safety

compromise. Could also be backed up by conventional

mechanical linkage during emergencies.

D. Performance - described in the following section.

IV. RESULTS

An analog simulation* incorporating a point source
visual projector for horizon presentation and cockpit instru-
ments to present airspeed, altitude, and engine power was
mechanized to measure pilot performance. Limitations in the
quantity of servo equipment available prevented simultaneous
simulation of both longitudinal and lateral-directional
modes of motion. Since longitudinal motion represents the
larger portion of the task of the pilot and since it requires
much more learning or skill on the part of the pilot, efforts
to measure performance were concentrated on this part. A
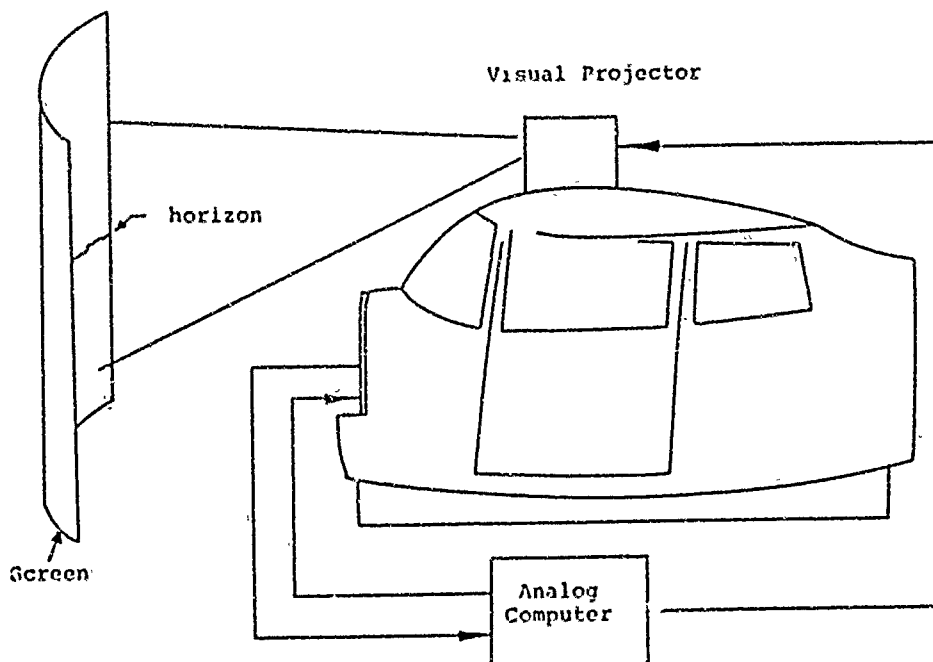sketch of the physical arrangement is shown in Fig. 10.

FIG. 10 - SIMULATOR SCHEMATIC

*Described in the Appendix

The task was organized to compare the performance of three test subjects when using a conventional control system (throttle, control column to deflect elevator, and flap deflection lever) and when using the proposed scheme of $\dot{\gamma}$ and $\dot{q}$ control. The flight profile specified as the test maneuver was as follows:

A. From a cruising flight condition of level flight at 4,000 ft altitude and 150 MPH, reduce speed to 120 MPH while maintaining altitude. Stabilize in this configuration.

B. Establish a climb at 120 MPH and climb to 5,000 ft altitude, maintaining airspeed and pitch attitude.

C. Level off at 5,000 ft; then, maintaining 120 MPH, establish a steady descent at approximately the same magnitude of vertical speed as was used in the climb.

D. Halt the descent at either 4,000 or 3,000 ft, at the pilot's discretion.

E. When established in level flight, increase speed to 150 MPH, maintaining altitude.

Test subjects were given several practice runs, and when they stated they were ready, three data runs were recorded in the form of time histories of V and h and sometimes additional parameters such as α, θ, and γ. The resulting data are not intended to be a complete statistical sample, simply enough to obtain consistency among the three test runs for each subject to indicate comparative performance.
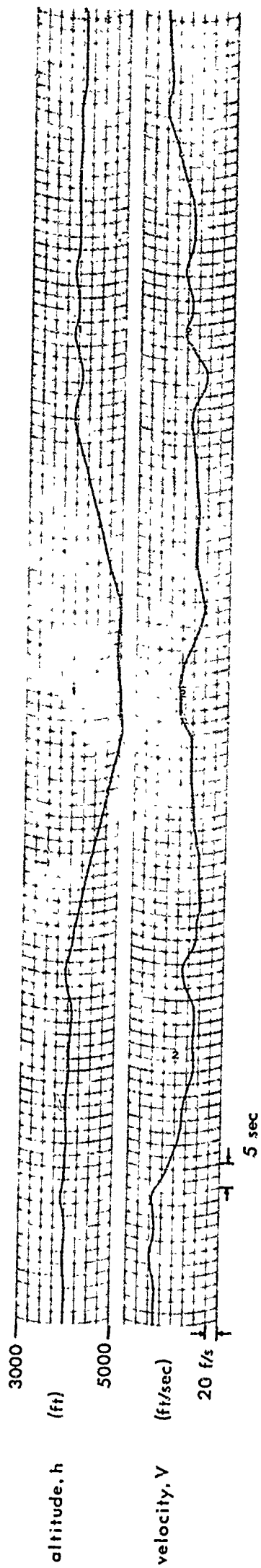
We will call the subjects 0, 1 and 40, indicating zero flight experience, 100 hours flight experience, and 4,000

hours flight experience. Figures 11a, b, c show represent-
ative performance by subjects 0, 1 and 40 respectively while
using the conventional control system. Figures 12a, b., c
show performance using the $\dot{\gamma}$-q system. As a measure of
pilot effort, time histories of pitch attitude using the
conventional and proposed control scheme are compared in
Fig. 13. Significant results indicated by the data are:

A. The performance of subject 0 using the proposed
control scheme is equal or superior to the per-
formance of subject 40 using a conventional control
system, in terms of mean square deviation from
the desired flight profile.

B. Pilot effort decreased sharply using the proposed
scheme.

C. Performance improvement varied inversely with
flight experience.

Subjective evaluation of the $\dot{\gamma}$-q control system can be
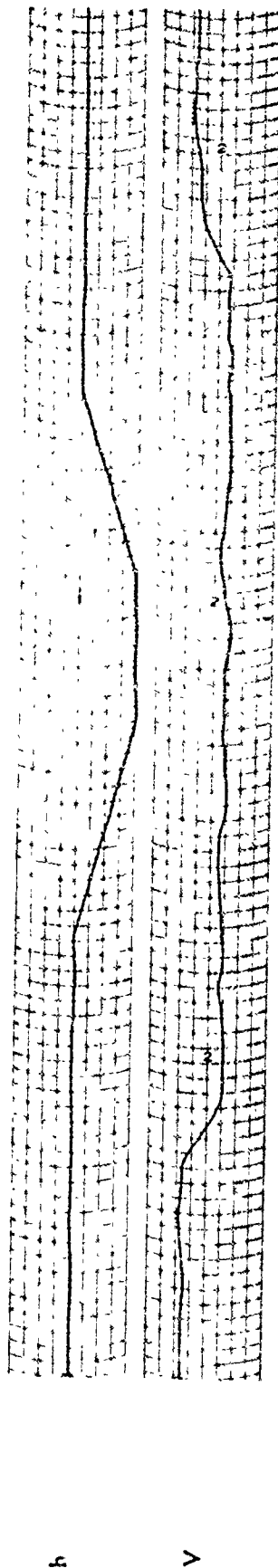determined by pilot comment:

Subject 0 - "I'm sure my performance was much better on
this airplane than the previous one. I was
able most of the time to execute the maneuver
with only one handle. On climb and descents
I could easily set up the climb angle and then
make minute adjustments to hold the airspeed.
At no time did I worry about the airspeed getting
out of hand due to a pitch change and conversely.
At no time did I get disoriented and attempt a
correction in the wrong direction. I did this
several times on the previous airplane. I think
I could do better with a smoother $\dot{\gamma}$ lever.
Several times I thought I was against a stop,

altitude, h   (ft)
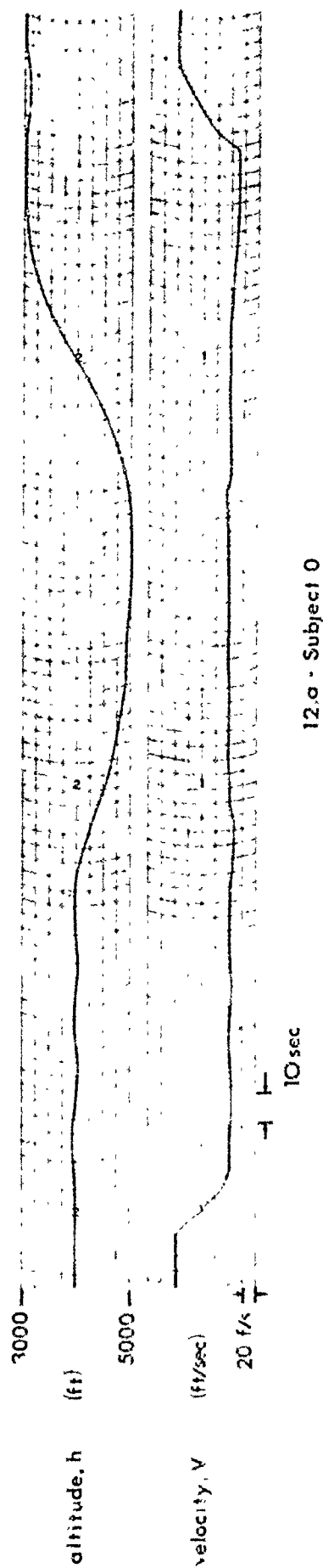
velocity, V   (ft/sec)

3000

5000

20 f/s

5 sec

11.a - Subject O

h

V

11.b - Subject 1

h

V

11.c - Subject 40

FIG. 11—PERFORMANCE WITH CONVENTIONAL CONTROL SYSTEM

altitude, h   (ft)

velocity, V   (ft/sec)

3000

5000

20 f/s

h

V

h

V

10 sec

12.a - Subject 0

12.b - Subject 1
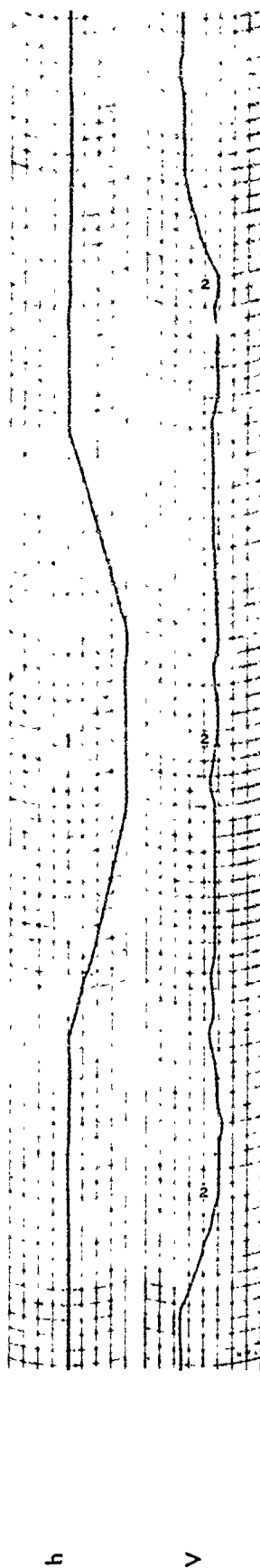
12.c - Subject 40

FIG. 12 — PERFORMANCE WITH $\dot{\gamma} - q$ CONTROL

then 'broke over' as the spring buckled. Air-
speed control was extremely easy requiring only
fingertip positioning. Altitude control was not
quite as easy, but far superior to the previous
airplane. It was several minutes before I began
to really use the horizon display in flying. It
was helpful when I began to use it. I had some
difficulty getting accustomed to the horizon
changes with airspeed at constant altitude."

Subject 1 - "I think my performance was better. It is easier
to fly, but I don't have the 'feel' of the air-
plane and I don't think I would get any 'feel'."

Subject 40- "The work load is down--it flies like a 180 with
a L-2 (autopilot)."

Miscellaneous other comment was given with a summary

statement from all the pilots that the proposed scheme was

much easier to fly and minimized the amount of concentration

required. It is emphasized that these tests are not intended

to be exhaustive statistical samples, only sufficient data

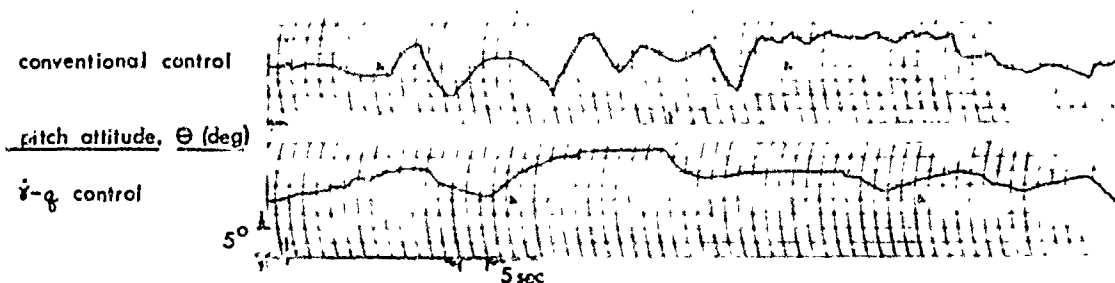to indicate the potential of the concept of direct flight

control.

FIG 13 - PITCH ATTITUDE COMPARISON AS A MEASURE OF PILOT EFFORT

(SUBJECT O)

V. CONCLUSION

While the simulation results are encouraging, actual flight evaluation is the only way to verify the apparent merits of direct flight control. In the opinion of the principal investigator, the most fruitful extension of this work would consist of a flight program with two major goals: First, verification of performance improvement obtained with $\dot{Y} - \dot{q} - \dot{\psi}$ controls; second, experimentation with various schemes which can act upon the information most easily measured in flight. The latter part would help establish the simplest, most reliable methods of providing flight control--a task where it is easy to be mislead when a purely theoretical approach is used. Certain simple theoretical concepts are quite difficult to implement while certain elaborate theorems are readily transferred to reality.

If the results obtained here are correct, extension to other or more sophisticated vehicles is readily achievable since nothing in the synthesis of this approach requires a certain range of aerodynamic or dynamic parameters. For example extension to a rotary-winged vehicle is possible; in fact, a helicopter embodies a measure of direct flight control already. The collective pitch control governs the magnitude of a force vector, the cyclic pitch control governs the direction of the force vector, and the pedals provide yaw motion. These controls must be coupled however and thus the task would resemble the one undertaken here.

Also, if the results obtained here are correct, additional
sophistication of the $\dot{\gamma} - \dot{\varphi} - \psi$ scheme could provide extra
features such as pressure altitude hold. Ground command
of flight path and speed via a radio link could achieve
traffic control for instrument flight.

It is believed that the greatest potential benefit
of direct flight control as evaluated here would be the
ease in learning to fly afforded by this scheme. This
also infers an ease in maintaining a desired level of
proficiency for the experienced pilot.

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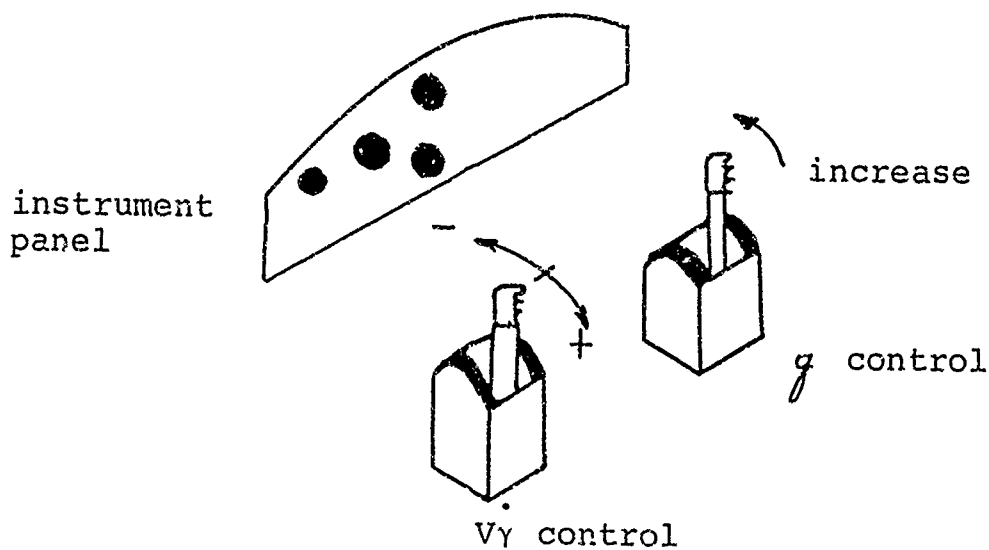
APPENDIX

A. Mathematical Model Used for Simulation

So as to insure accurate simulation of the flight
dynamics of the airplane being simulated (a Cessna 180),
a non-linear force and moment model was used rather than a
small-perturbation-from-equilibrium, linearized model.
This method afforded the retention of dimensional variables
and permitted a range of flight velocities of from 10 ft/sec
to 300 ft/sec. Aerodynamic derivatives and mass and inertia
parameters were obtained from Cessna Aircraft Company as
presented in company reports (Ref. 3, 4).

B. Visual Presentation and Cockpit Equipment

A point source projector mounted in a gimbal frame
atop the cockpit presented a horizon which tilted with the
aircraft motion. A blue sky--green and brown earth picture
which did not show translation was deemed realistic enough
for this project. Within the cockpit an instrument panel
included an airspeed indicator, an altimeter, and an engine
power gage. For the conventional control scheme a standard
control wheel and throttle were used, while for the proposed
scheme two levers were mounted in front of the pilot, as
shown below. The right-hand lever functioned as the g-
control and friction was incorporated in the mechanism to
make the lever stay where it was placed. On the left the

lever which controlled $V\gamma$ was spring loaded to maintain a center position when released. A dead zone was synthesized about this position so as to insure the ability to return to $\dot{\gamma} = 0$ in the presence of system friction. Outside the dead zone a force proportional to lever deflection--hence proportional to $|\dot{\gamma}|$--existed.

instrument panel

increase

$\dot{g}$ control

$V\dot{\gamma}$ control

Cockpit Arrangement of the $\dot{\gamma}$-$\dot{g}$ Control System